IGM88RT-107,109,206-756-G
CNRC 29105

A STRATEGY FOR EXPERIMENTS TO DEVELOP AND VERIFY PROCESS SIMULATION SOFTWARE

BY

G. Salloum, L. P. Hebert

NATIONAL RESEARCH COUNCIL CANADA
INDUSTRIAL MATERIALS RESEARCH INSTITUTE
BOUCHERVILLE, QUEBEC

25 July 1988

TABLE OF CONTENTS

1 INTRODUCTION 1

2 THE FOUR RESEARCH AND DEVELOPMENT AREAS 1
2.1 DEVELOPMENT AND VERIFICATION OF FILLING MODELS . . 1
2.2 DEVELOPMENT AND VERIFICATION OF COOLING AND SOLIDIFICATION MODELS 1
2.3 DEVELOPMENT AND VERIFICATION OF SHRINKAGE MODELS . 3
2.4 DEVELOPMENT AND VERIFICATION OF MATERIAL PROPERTY MODELS 3

3 PROBLEM DEFINITION 3
3.1 PRIMARY PROBLEM 3
3.2 IMPORTANT FACTORS 3
3.3 DOCUMENTATION OF EXPERIMENTS 3

4 TASK 1: PROCESS SIMULATION ANALYSES 4
4.1 INFORMATION REQUIRED FOR PROCESS SIMULATION . . . 4
4.1.1 INFORMATION REQUIRED ABOUT MATERIAL PROPERTIES . 4
4.1.2 INFORMATION REQUIRED ABOUT TEST MOULDS 4
4.2 PROCESS SIMULATION TO BE PERFORMED 4
4.3 INFORMATION GENERATED BY THE PROCESS SIMULATION . 5

5 TASK 2: EXECUTION OF AN EXPERIMENT 5
5.1 STABILIZATION OF PROCESS PARAMETERS 5
5.2 PRELIMINARY EXPERIMENTS FOR FAMILIARIZATION . . . 5
5.2.1 SPECIMEN QUALITY CONTROL 6
5.3 CREATION OF A STATISTICALLY DESIGNED EXPERIMENT . 6
5.4 EXECUTION OF THE STATISTICALLY DESIGNED EXPERIMENT 6
5.4.1 SAMPLING OF SPECIMENS 6
5.5 LONG TERM STORAGE OF SPECIMENS 6

6 TASK 3: ANALYSIS OF THE DATA 7

7 CONCLUSION 7

APPENDIX A STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS

A.1 GOALS OF STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS 8
A.2 SOFTWARE TOOLS FOR STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS 8
A.3 STAGES IN THE EXECUTION OF AN EXPERIMENT 9
A.3.1 FAMILIARIZATION 9
A.3.2 SCREENING 9
A.3.3 EMPIRICAL MODELING 9

APPENDIX B DEFINITIONS

B.1 TERMS FOR STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS 10

1 INTRODUCTION

Due to the substantial number of experiments required for the development of CIMP technology which are performed in IMRI's laboratories or with our partners in industry and universities, the need for a strategy describing in general terms the design and execution of experiments becomes evident. The purpose of this STRATEGY FOR EXPERIMENTS TO DEVELOP AND VERIFY PROCESS SIMULATION SOFTWARE (see Fig. 1) is:

1) to speed the development of technology

2) to eliminate duplicated experimentation and to increase the availability of processing equipment at IMRI

3) to generate the maximum amount of information related to each of the FOUR RESEARCH AND DEVELOPMENT AREAS from each experiment

4) to compare as well as verify the accuracy of the various simulation programs by:

a) Understanding which **factors** (1) affect the **response**(s) most significantly, so as to eliminate unimportant **factors**
b) Characterizing the effects of the **factors** on the **response**(s)
c) Optimizing the **factors** so as to obtain the desired **response**(s)

It should be noted that each process (e.g. injection moulding, extrusion, die casting, ...) has distinct characteristics which may not be addressed in this strategy.

2 THE FOUR RESEARCH AND DEVELOPMENT AREAS

This section describes the information required from each experiment.

2.1 DEVELOPMENT AND VERIFICATION OF FILLING MODELS

Example for injection moulding.

The models for injection moulding may include solid layer formation during filling. The shape of flow front in short shots and the measurement of cavity pressures and melt temperatures during the injection of complete parts will provide the required information.

2.2 DEVELOPMENT AND VERIFICATION OF COOLING AND SOLIDIFICATION MODELS

Example for injection moulding.

(1) Terms in bold characters, such as **factor**, are defined in appendix B.

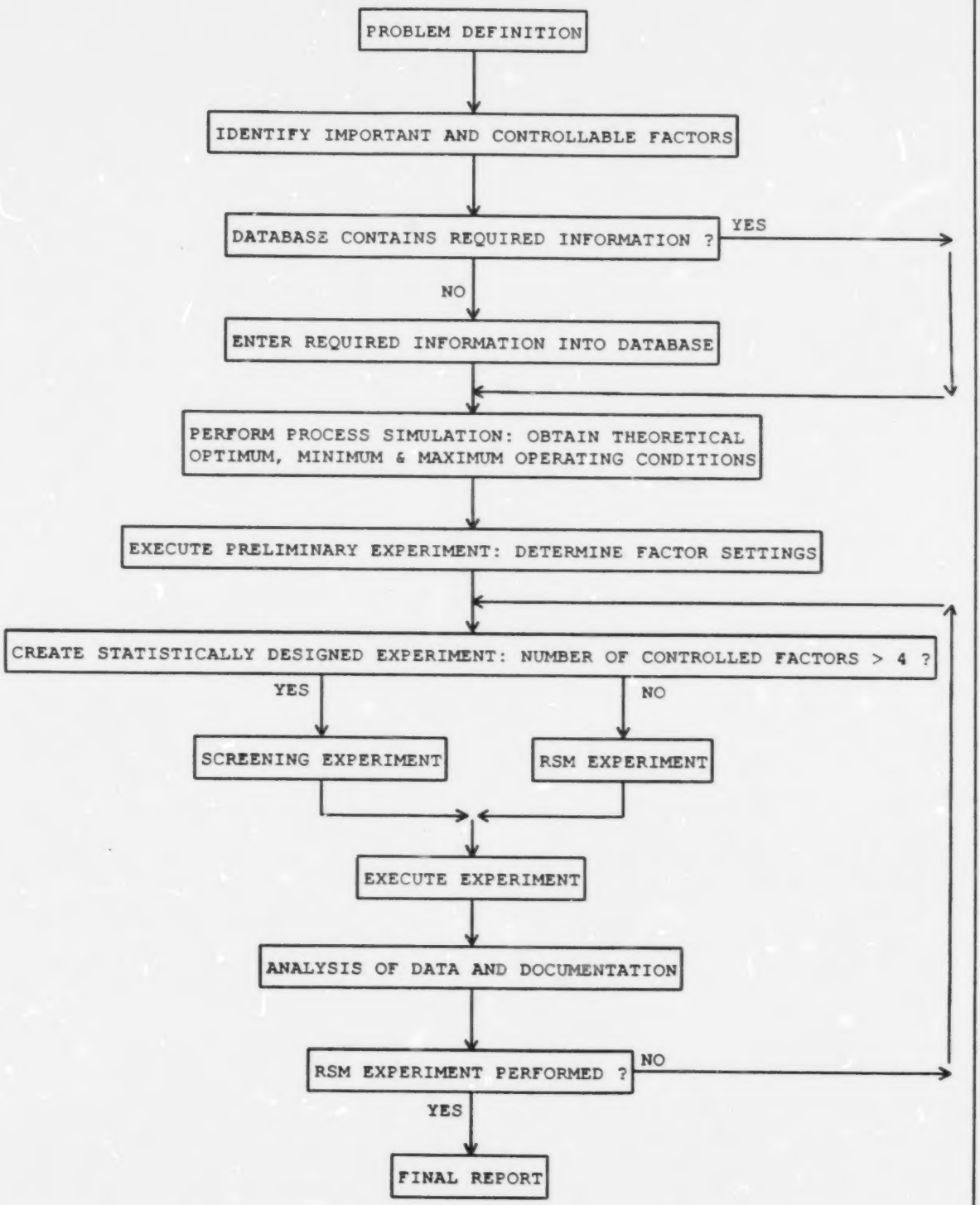

FIG. 1: TASK FLOW CHART

Moulding specimens below the minimum processing parameters (e.g. low injection speed, low melt temperature, low mould temperature) will result in the flow front solidifying before the cavity is filled. Comparison of the actual versus theoretical position of the solidified flow front will provide the required information.

2.3 DEVELOPMENT AND VERIFICATION OF SHRINKAGE MODELS

The dimensions of specimens are required for the calculation of radial, longitudinal or transverse shrinkages.

2.4 DEVELOPMENT AND VERIFICATION OF MATERIAL PROPERTY MODELS

ASTM specimens should be tested so as to measure material properties for inclusion in the material database.

3 PROBLEM DEFINITION

3.1 PRIMARY PROBLEM

Each experiment begins with a PROBLEM DEFINITION, typically directly related to one of the FOUR RESEARCH AND DEVELOPMENT AREAS previously described.

Each experiment must provide, as far as possible, information that can be used for the FOUR RESEARCH AND DEVELOPMENT AREAS previously described. To achieve this objective, researchers and technologists involved in all of the FOUR RESEARCH AND DEVELOPMENT AREAS, for a particular process, should participate in the planning of the experiment.

3.2 IMPORTANT FACTORS

Based on the **investigators'** knowledge of the process, the **factors** to be studied are selected. All **factors** which may have an effect should be included, since variations in the missing **factors** may cause the **response**(s) to be erratic.

The selected **factors** will include most process parameters. **Factors** other than process parameters may be required in certain cases. Process parameters which are not considered to have any effect on the **response**(s) will be set to constant levels specified by the **investigators**.

3.3 DOCUMENTATION OF EXPERIMENTS

Each experiment must be documented as work is completed. The documentation must include such information as mould identification, analyses executed, verifications of process simulations, experimental designs, specimens produced, production times and dates of specimens and measurements performed.

4 TASK 1: PROCESS SIMULATION ANALYSES

This section describes the analyses of the process required before specimens are produced for an experiment. One of the principal purposes of the simulations is to determine the settings of the factors or processing parameters that will produce acceptable part.

4.1 INFORMATION REQUIRED FOR PROCESS SIMULATION

4.1.1 INFORMATION REQUIRED ABOUT MATERIAL PROPERTIES -

The material properties must be available in the material database, so that the process can be properly simulated. For example, filling simulations require specific heat, density, thermal conductivity, viscosity, thermal diffusivity.

4.1.2 INFORMATION REQUIRED ABOUT TEST MOULDS -

Example for injection moulding.

1) dimensions of runners, gates and cavities

2) dimensions and locations of ejection pins

3) dimensions and locations of cooling channels

4) description and location of pressure transducers and temperature sensors

The TEST MOULDS used for the production of specimens are:

1) MODUMOULE, with various gates, thicknesses and inserts

2) ASTM, with various gates and thicknesses

3) other test moulds (from industry or universities)

4.2 PROCESS SIMULATION TO BE PERFORMED

Example for injection moulding.

1) flow front positions and shapes

2) pressure losses in the cavity, including moulding parameters that will cause the mould to open, resulting in flashing

3) cooling and solidification, including moulding parameters that will result in the flow front solidifying before the cavity is filled

4.3 INFORMATION GENERATED BY THE PROCESS SIMULATION

The processing parameters generated by the process simulation are theoretical values that must be verified by the experiments.

Example for injection moulding.

1) Optimum processing parameters.

2) Processing parameters that will result in the flow front solidifying before the cavity is filled; for the development and verification of COOLING AND SOLIDIFICATION MODELS.

3) Minimum processing parameters without short shots; for the estimation of the minimum **factor** values for the STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS.

4) Maximum processing parameters without flashing; for the estimation of the maximum **factor** values for the STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS.

5 TASK 2: EXECUTION OF AN EXPERIMENT

This section describes the steps required for the execution of an experiment. If possible, statistical quality control (SQC) data must be collected during all stages of the experiment.

Example for injection moulding.

For all specimens, typical graphs of cavity pressure versus screw position must be recorded.

5.1 STABILIZATION OF PROCESS PARAMETERS

Sufficient time for the process to stabilize should be allowed when processing parameters are varied. For example, 20 to 30 minutes may be required for a material's temperature to stabilize, whereas changes in the injection speed of an injection machine may require 3 to 5 minutes.

5.2 PRELIMINARY EXPERIMENTS FOR FAMILIARIZATION

Some preliminary specimens are made so as to verify the minimum and maximum values of **factor** settings determined from the INFORMATION GENERATED BY THE PROCESS SIMULATION. Once these **factor** values are determined, specimens for the COOLING AND SOLIDIFICATION and the FILLING MODELS must be made.

5.2.1 SPECIMEN QUALITY CONTROL -

The parts should be free of any visual defects, such as sink marks, burns, flash, warpage, streaks, bubbles, cracks, crazing, flow lines, poor weld lines and surface finish, etc...

The part weights' should be as constant as possible; typically, the weight should not vary by more than 2 percent between different **experimental runs**. The reference part weight should be determined from the cavity volume, taking into account the typical shrinkage for the resin as indicated in the manufacturer's specification sheet, and the resin's average density.

Where possible, the parts must have a low level of residual stresses.

Example for injection moulding

When parts are annealed 48 hours after moulding, their dimensions should not change by more than 0.2%.

5.3 CREATION OF A STATISTICALLY DESIGNED EXPERIMENT

Using the experimentally determined minimum and maximum values of **factor** settings, create a statistically designed experiment. Based on the number of **factors**, select a **SCREENING** or a **RSM** experiment.

5.4 EXECUTION OF THE STATISTICALLY DESIGNED EXPERIMENT

Produce specimens using the values of **factors** in the experiment design of the previous step.

5.4.1 SAMPLING OF SPECIMENS -

The researchers responsible for each of the four research and development areas (cooling and solidification models, filling models, shrinkage models and material property models) will specify their requirements for specimen sampling and measurements.

5.5 LONG TERM STORAGE OF SPECIMENS

Specimens that are not required for storage can be recycled if possible or discarded. Two specimens per cavity and per **experimental run** must be stored.

6 TASK 3: ANALYSIS OF THE DATA

After measuring the **response**(s), the data must be analysed. Generally speaking, the experimental results must be compared to the results of the various simulations.

If the **factors** which affected the **response** the most were identified in a **SCREENING** experiment, a **RSM** experiment may be desired; in this case, another experiment must be designed and executed.

7 CONCLUSION

The methods described in this strategy are recommendations. We hope that this report will result in enhanced communication among all of the **investigators** during the design and execution of experiments at IMRI and with our partners. The reasons why the experiments are to be performed in certain manners will be understood by all. The ultimate goal is to avoid duplication of experiments and thus accelerate the development of technology.

APPENDIX A

STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS

This appendix defines STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS.

A.1 GOALS OF STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS

The goals of statistical experimental design and analysis are:

1) Understanding which **factors** affect the **response**(s) most significantly, so as to eliminate unimportant **factors** (**SCREENING**)

2) Characterizing the effects of the **factors** on the **response**(s) (**RSM**)

3) Optimizing the **factors** so as to obtain the desired **responses** (**RSM**)

A.2 SOFTWARE TOOLS FOR STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS

RS/DISCOVER is used to design and analyse both **SCREENING** and **RSM** experiments. It is also capable of both statistical analyses and regressions involving multiple **factors**. This software tool is an interactive program.

RS/EXPLORE is used for statistical analyses and for exploring the relationship between one or two **factors** and a **response**. This software tool is an interactive program.

SAS is used for statistical analyses and regressions involving multiple **factors**. The present version of this software tool is non-interactive and requires programming.

A.3 STAGES IN THE EXECUTION OF AN EXPERIMENT

A.3.1 FAMILIARIZATION

Some preliminary specimens are made so as to verify the minimum and maximum values of **factor** settings determined that produce barely acceptable parts.

A.3.2 SCREENING

In the case where the list of potentially important **factors** is large, (greater than three **factors**), a series of **screening** experiments can be used to select the **factors** with the greatest effects on the **response**(s).

In the case where the list of potentially important **factors** is small, **screening** experiments need not be done.

A.3.3 EMPIRICAL MODELING

Once the **factors** with the greatest effects on the **response**(s) have been identified, it is possible to build a mathematical model to predict the **response** from the values of **factors**. These mathematical models can be linear, interaction, quadratic, cubic or user-defined in nature. These models are based on regressions analyses.

Empirical modeling is also called **RESPONSE** SURFACE MODELING (**RSM**), since the empirical models are often visualized as two or three dimensional graphs.

The mathematical model can be used to predict and optimize the **responses**.

APPENDIX B

DEFINITIONS

B.1 TERMS FOR STATISTICAL EXPERIMENTAL DESIGN AND ANALYSIS

EXPERIMENTAL RUN refers to a group of specimens created while the process parameters are held constant. An EXPERIMENT refers to a group of **EXPERIMENTAL RUN**S.

FACTOR or input variable refer to parameters that may affect the **response**(s). Obviously, process parameters, such as material temperature, are **factors**.

INVESTIGATORS refers to all persons with knowledge of the **factors** and **responses**: scientists, engineers, technicians and end users.

RESPONSE or output variable refer to a specimen characteristic, such as modulus. **Responses** can be quantitative or qualitative.

RSM (**RESPONSE** SURFACE MODELING) or empirical modeling experiments determine the relationships between **factors** and **responses**, using multiple variable regression analysis techniques. For example, a regression equation to predict the shrinkage of a part from the values of the moulding parameters.

SCREENING experiment determines which **factors** have the greatest effect on the **response**(s).